

Mars' Ancient Dynamo and Crustal Remanent Magnetism

*A whitepaper submitted to the 2011 Planetary Science Decadal Survey
(names in **red** have not yet accepted)*

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Executive Summary

At present, Mars has no core dynamo nor associated global magnetic field. The strong crustal remanent magnetic fields imply that a dynamo once existed, likely ceasing ~4 Gyr ago, exposing the atmosphere to stripping by the solar wind and quite possibly affecting climate evolution. The pattern of crustal magnetic fields (and hence subsurface magnetization) has likely been significantly altered by impact, fluvial, hydrothermal, tectonic and volcanic processes over the planet's history. Although we have learned much from the Mars Global Surveyor (MGS) Magnetometer/ Electron Reflectometer (MAG/ER) experiment, most measurements thus far have been fundamentally limited by their great distance from magnetic sources. Hence, many questions remain about the spatial distribution, direction, strength, depth and mineral carrier(s) of the crustal magnetization and the strength, nature and duration of the ancient core dynamo. **To address these questions, we recommend to the 2011 Decadal Survey that NASA:**

- **Support an extended MAVEN mission with a low periapsis (150 km), magnetometer measurements from which will enable interpretation of the magnetic signatures of smaller geologic features (e.g. craters, rifts, volcanoes) than is currently possible.**
- **Investigate placing a dual-magnetometer system on a rover sent to a region of known strong magnetic anomalies. It should be mounted such that rover-generated fields can be mitigated and the remanent field measured accurately.**
- **Investigate placing a magnetometer on an aircraft or long-lived balloon-craft to obtain low-altitude magnetic measurements over tens or hundreds of kilometers.**
- **Begin planning for the return to Earth of oriented Noachian bedrock samples in magnetically-shielded containers for magnetic and radioisotope analysis in terrestrial laboratories.**

Value

Determining the nature and origin of Mars' crustal remanent magnetization will provide valuable knowledge pertinent to three major questions in Mars science:

- 1) The formation and evolution of the crust, including its mineralogy and modification, during the past ~4.5 Gyr, by tectonic, impact, fluvial, hydrothermal and magmatic processes.
- 2) The evolution of the interior, including early global heat flow and the history and lifespan of convection within the core (i.e. by studying the history of the dynamo).
- 3) The evolution of climate and habitability, particularly the stability of surface water, which are constrained by the lifespan of the global magnetic field (and the shielding it provided against solar wind stripping of the atmosphere).

Current knowledge of Mars crustal magnetism & ancient Dynamo

Unexpectedly strong crustal fields: The era of Mars crustal magnetism began in 1997, when intense, localized magnetic fields (up to 1500 nT at 100 km) were discovered by the MGS MAG/ER experiment (figure 1). These fields are several orders of magnitude stronger than lunar crustal fields and are roughly one order of magnitude stronger than terrestrial crustal fields. They

are consistent with large volumes (up to $\sim 10^6 \text{ km}^3$) and thicknesses (up to 50 km) of coherently magnetized crust, with remanent magnetizations of tens of A/m [Acuña et al., 1999], which are the lithospheric remnant of a strong Martian global field, and therefore a core dynamo, in the past.

Magnetic mapping and global distribution of magnetic fields: 9 years of crustal magnetic field measurements from the MGS MAG (vector measurements sparsely down as low as 90 km, but mostly at 400 km) and MGS ER (remote measurements of total field magnitude at 185 km) have been used extensively for geophysical interpretation of impact, fluvial, tectonic and volcanic features, whose formation processes modified the crustal magnetization pattern [Acuña et al., 1999; Connerney et al., 1999, 2001; Arkani-Hamed, 2004; Lillis et al., 2006, 2008a; Johnson and Phillips, 2005; Whaler and Purucker, 2005; Mitchell et al., 2007, Shahnas and Arkani-Hamed, 2007; Hood et al., 2001, 2003; Langlais et al., 2004; McEnroe et al., 2004, Milbury et al., 2007; Nimmo and Gilmore, 2001; Voorhees, 2008].

To first order, the global crustal field pattern follows the dichotomy boundary, with the older, heavily-cratered Noachian surface south of the boundary displaying much stronger crustal fields than the less-cratered northern lowlands. This pattern may be due to hemispheric differences in crustal thickness [Neumann et al., 2004], core dynamo field strength [Stanley et al., 2008] and/or serpentinization [Quesnel et al., 2009]. The true cause is unclear.

Modification of magnetization by tectonic, magmatic and impact processes: The linear pattern of the radial crustal magnetic fields in Terra Cimmeria and Terra Sirenum (lower middle of the map in figure 2) has been interpreted as being reminiscent of plate tectonic activity early in Mars' history [Connerney et al., 2001; 2005], though this suggestion remains debatable since compact sources of magnetization, rather than elongated ones, can also account for this linear pattern [Hood et al., 2007; Jurdy and Stefanick, 2004].

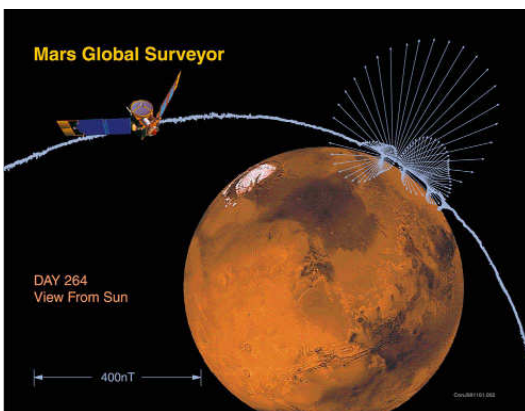


Figure 1: MGS aerobraking pass with magnetic field vectors emanating from spacecraft position, demonstrating the crustal origin of the strong magnetic fields.

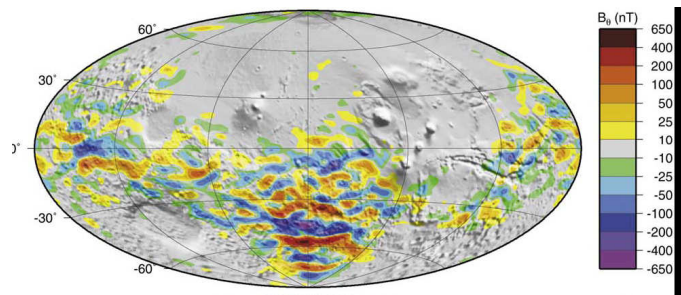


Figure 2: map of the radial component of Mars' crustal magnetic field at 200 km altitude from the equivalent source dipole model of Langlais et al. [2004], which is based on 5 years of MGS magnetometer data.

Extremely weak fields are measured over the large volcanic provinces Elysium and Tharsis, suggesting post-dynamo thermal demagnetization by long-lived pervasive magmatism [Johnson and Phillips, 2005; Lillis et al., 2009] while somewhat stronger fields have been measured over the older and smaller highland volcanoes [Lillis et al., 2006; Langlais and Purucker, 2007].

Very weak or nonexistent crustal fields are measured within the 5 youngest large ($>1000 \text{ km}$) impact basins, implying shock and thermal demagnetization by impact processes [Hood et al.,

2003; Mohit and Arkani-Hamed, 2004; Lillis et al., 2008b]. In contrast, the 14 oldest identified large impact basins all have moderate-to-strong magnetic fields within. Analysis of basin ages and magnetic signatures suggests a rapid decrease in post-impact crustal magnetization within these basins around a model age of ~4.1 Gyr [Lillis et al., 2008b].

The Martian dynamo: The most straightforward explanation of the sudden decrease in crustal magnetization is that turbulent core convection became no longer vigorous enough to sustain a global magnetic field [Acuña et al., 1999; Arkani-Hamed, 2004, Lillis et al., 2008a,b], thereafter exposing the upper atmosphere to being stripped away by the solar wind [Jakosky et al., 1994]. This rapid cessation is consistent with Mars core dynamo simulations [Kuang and Jiang, 2008].

Paleomagnetic pole positions: paleopole positions, calculated by assuming that certain magnetic anomalies are due to a single coherently magnetized source, cluster in or near a region northwest of Olympus Mons [Arkani-Hamed, 2001; Arkani-Hamed and Boutin, 2004; Hood et al., 2005], suggesting a possible reorientation of Mars' rotation axis, a conclusion supported by other independent studies [e.g. Perron et al., 2007].

Evidence from Martian meteorites: Martian meteorites provide direct sampling of Martian magnetization, for which magnetic fields are a (sometimes rough) proxy. Analysis of the oldest known meteorite from Mars, ALH 84001, indicates that the meteorite's remanence is carried primarily by magnetite and that the paleofield on Mars ~4 Ga was likely similar to that on the Earth presently [e.g., Weiss et al., 2008], which is consistent (within errors) with the aforementioned giant basin magnetic field signatures.

Candidate magnetic minerals: for the dominant Martian magnetic mineral, there are 4 other candidates. Titanohematite, which is very stable for slow cooling and high lithostatic pressures, is an attractive candidate for deep-seated crustal sources. Titanomagnetite is magnetically much softer and a less-likely candidate except in the case of anisotropic stresses or nanoscale exsolution. Pyrrhotite is an important magnetic carrier in the basaltic shergottite meteorites [e.g., Rochette et al., 2001], but has a low blocking temperature (320°C) and so cannot easily be responsible for deep sources [e.g. Dunlop Arkani-Hamed, 2005]. Lamellar hematite-ilmenite has also been proposed based its role in intense terrestrial anomalies [McEnroe et al., 2004]

Outstanding questions

Despite what we have thus far learned about Mars' crustal remanent magnetism and ancient dynamo, we have been mostly limited to remote observations of magnetic fields, most of which have been ~200 km or more from their sources and the interpretation of which suffers from inherent non-uniqueness (which increases with distance). **Much of the evidence for what we believe is circumstantial because we lack 'ground truth' for crustal magnetization, in terms of its strength, direction, age or mineral carrier.** The three major outstanding questions are:

- 1) What is/are the major carrier(s) of Martian crustal magnetization?
 - a. What are their domain states?
 - b. When, in what type of environment and through what processes did they form?
- 2) What are the properties of the source bodies responsible for Mars' remarkable crustal magnetic fields?
 - a. What is the lateral scale of these bodies and what does this tell us about their formation processes?

- b. What is their maximum depth and what does this tell us about the thermal gradient in the crust when they formed?
 - c. What are their formation ages?
- 3) What were the characteristics of Martian dynamo?
 - a. How soon after accretion did it start?
 - b. Did it ever stop and restart?
 - c. When did it cease permanently and how quickly did this happen?
 - d. What was the average surface field strength and did it vary over time?
 - e. Was the field aligned with the rotation axis?
 - f. Was it dominantly dipolar or did it have substantial higher order terms?
 - g. Did it reverse polarity and if so, how frequently and what were the characteristics of the reversals (duration, global field weakening)?

Currently planned measurements

The MAVEN Mars Scout's 365-day nominal mission consists of ~2000 orbits with periapsis at 150 km, plus 125 orbits at 120 km. Its orbit is due to precess naturally so that a mission extension of 2-4 years will provide effectively global vector magnetic field coverage at ~150 km. While measurements from the nominal mission will be useful in improving the quality of models of the Martian crustal magnetic field, a significant extended mission will enable a comprehensive study of the magnetic field signatures of significantly smaller geological features (e.g. impact craters, volcanoes) than is currently possible. **However, magnetic field measurements taken from orbit will not by themselves enable us to solve the outstanding questions about Mars' crustal remanent magnetism and the ancient dynamo.**

Recommendations for future measurements

Recommendation #1: extend MAVEN's mission with as low a periapsis as possible

- Because any orbiter with a periapsis below ~150 km requires constant DSN coverage (which is expensive and impractical over a long mission), the most cost effective way to achieve the best possible global knowledge of Mars' crustal magnetic fields is for NASA to extend the MAVEN mission well beyond the currently planned 365 days. Such global coverage will provide further constraints on crustal evolution and history of the ancient dynamo.
- MAVEN can still function as an effective relay for surface assets in such a low-periapsis orbital configuration.

Recommendation #2: surface and/or aerial magnetometer survey

We recommend that a **flux-gate magnetometer be mounted on a mobile surface and/or low altitude platform** to allow continuous measurements of crustal magnetic fields.

- One straightforward idea would involve a long boom on a magnetically clean rover. However some progress could be made using a dual-magnetometer system with only a short boom, by using the inboard magnetometer measurements to subtract the rover-

generated fields from the outboard magnetometer signal, as demonstrated in space on the non-magnetically-clean spacecraft Venus Express (Zhang et al, 2008).

- **The recently-canceled stationary magnetometer (MSMO) on the ESA ExoMars mission (launch in 2016) should be replaced by a NASA-funded magnetometer system mounted on the rover instead of the stationary lander.**
- Beyond a rover, for increased spatial coverage of tens or hundreds of kilometers, we recommend a magnetometer mounted on an aircraft (figure 3) or ballooncraft.

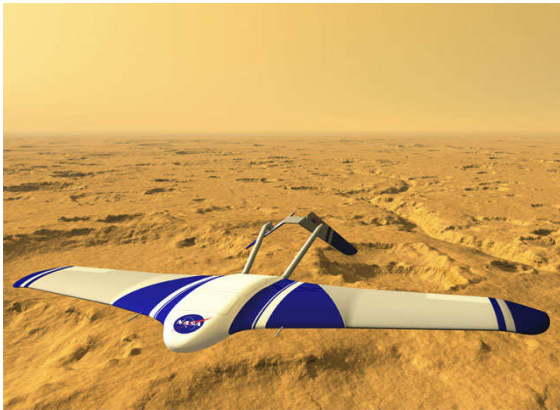


Figure 3: ARES concept for a low altitude Mars aircraft that could carry a magnetometer over a substantial distance.

- For either of the above, terrestrial experience in magnetic surveys will enable us to:
 - a) Characterize contrasts in Mars' crustal magnetization down to kilometer scales.
 - b) Much more accurately estimate the depth and thickness of the magnetized crust.
 - c) Accurately judge the potential of strong field regions for shielding the surface (and hence life and human explorers) from cosmic rays and solar energetic particles.
- Using a robotic arm to bring individual oriented rock samples close to the magnetometer, then rotating them, would determine the macro-scale total magnetization strength and direction of the

rock, while an alpha particle x-ray spectrometer could detect its magnetic minerals. Though not nearly as scientifically fruitful as sample return, this magnetometer-plus-robotic arm surface package would help answer several of the outstanding questions about Mars crustal magnetism for relatively modest cost.

Recommendation #3: sample return of Noachian crust

We recommend direct magnetic and radioisotope analysis of oriented Martian bedrock samples (i.e. samples whose original orientation is known), preferably in areas of Noachian crust, in terrestrial laboratories. We recognize that this will require sample return from the surface of Mars, an expensive and technologically challenging undertaking. However, the wealth of experience in radioisotope dating and paleomagnetism will enable us to determine or at least estimate:

- The mineral carrier of the remanence and its domain state (e.g. single domain magnetite, multi-domain hematite etc.).
- The strength and direction of the sample's magnetization and hence the strength and (with caveats) the paleopole location of the global magnetic field that magnetized it.
- The type of magnetic remanence (e.g. shock, chemical, thermal) and hence conditions under which it formed.
- The age of the magnetic inclusions and hence the time at which the magnetization was acquired.

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